

# Pulsed Airborne Lidar Measurements of Atmospheric CO<sub>2</sub> Column Absorption & lineshapes from 3-13 km altitudes

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*Presentation to:*

NASA Terrestrial Ecology Meeting

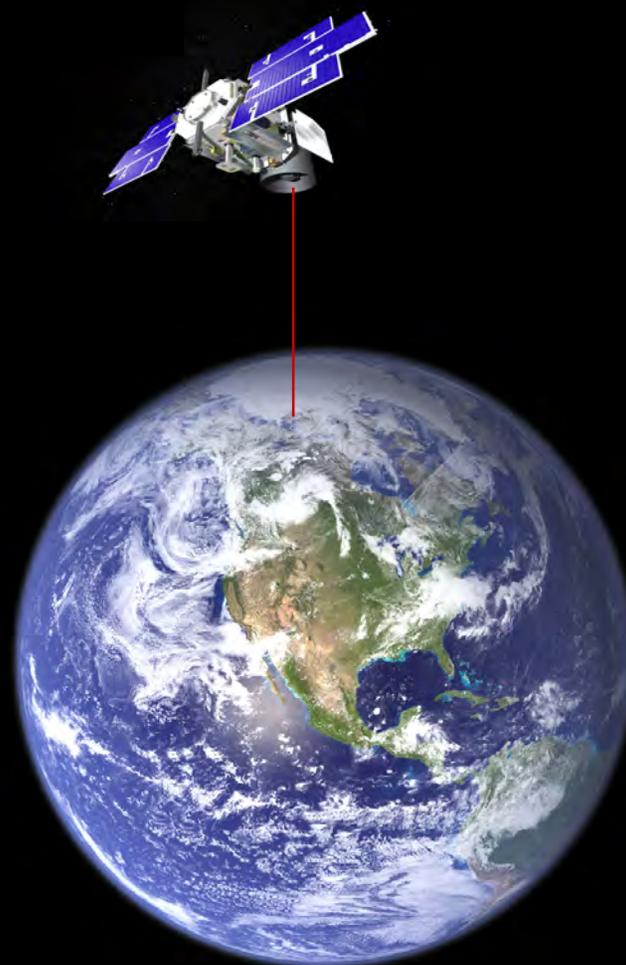
La Jolla, CA

March 15, 2010

Supported by:

NASA ASCENDS, ESTO IIP program, Goddard IRAD programs

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# Abstract



We have developed a lidar technique for measuring the tropospheric CO<sub>2</sub> concentrations as a candidate for NASA's planned ASCENDS mission. Our technique uses two pulsed laser transmitters allowing simultaneous measurement of a CO<sub>2</sub> absorption line in the 1570 nm band, O<sub>2</sub> extinction in the Oxygen A-band and surface height and backscatter. The lidar measures the energy and time of flight of the laser echoes reflected from the atmosphere and surface. The lasers are stepped in wavelength across the CO<sub>2</sub> line and an O<sub>2</sub> line region during the measurement. The receiver uses a telescope and photon counting detectors, and measures the background light and energies of the laser echoes from the surface along with scattering from any aerosols in the path. The gas extinction and column densities for the CO<sub>2</sub> and O<sub>2</sub> gases are estimated from the ratio of the on- and off- line signals via the DIAL technique. Time gating is used to isolate the laser echo signals from the surface, and to reject laser photons scattered in the atmosphere.

We have developed an airborne lidar to demonstrate the CO<sub>2</sub> measurement from a Lear-25 aircraft. The lidar steps the pulsed laser's wavelength across a selected CO<sub>2</sub> line with 20 steps per scan. The line scan rate is 450 Hz and laser pulse widths are 1 usec. The time resolved laser backscatter is collected by a 20 cm telescope, detected by a photomultiplier and is recorded by a photon counting system. We made initial airborne measurements on flights during fall 2008. Laser backscatter and absorption measurements were made over a variety of land and water surfaces and through thin clouds. Atmospheric CO<sub>2</sub> column measurements using the 1572.33 nm CO<sub>2</sub> line. Two flights were made above the DOE SGP ARM site at altitudes from 3-8 km. These flights were coordinated with investigators who flew an in-situ CO<sub>2</sub> sensor on a Cessna aircraft under the path. The increasing CO<sub>2</sub> line absorptions with altitudes were evident and comparison with in-situ measurements showed agreements to 6 ppm.

During summer 2009 we made 9 additional flights and measured the atmospheric CO<sub>2</sub> absorption and line shapes using the 1572.33 nm line. Measurements were made at stepped altitudes from 3-13 km over a variety of surface types in Nebraska, Illinois, the SGP ARM site, and near the Chesapeake Bay in North Carolina and Virginia. Strong laser signals and clear line shapes were observed at all altitudes. Some measurements were made through thin clouds. The flights over the ARM site were underflown with in-situ measurements made from the DOE Cessna. The Oklahoma and east coast flights were coordinated with a LaRC/ITT CO<sub>2</sub> lidar on the UC-12 aircraft, an in-situ CO<sub>2</sub> sensor, and the Oklahoma flights also included a JPL CO<sub>2</sub> lidar on a Twin Otter aircraft. More details of the flights, measurements and analysis will be described in the presentation.



# Laser Sounder Approach for ASCENDS Mission



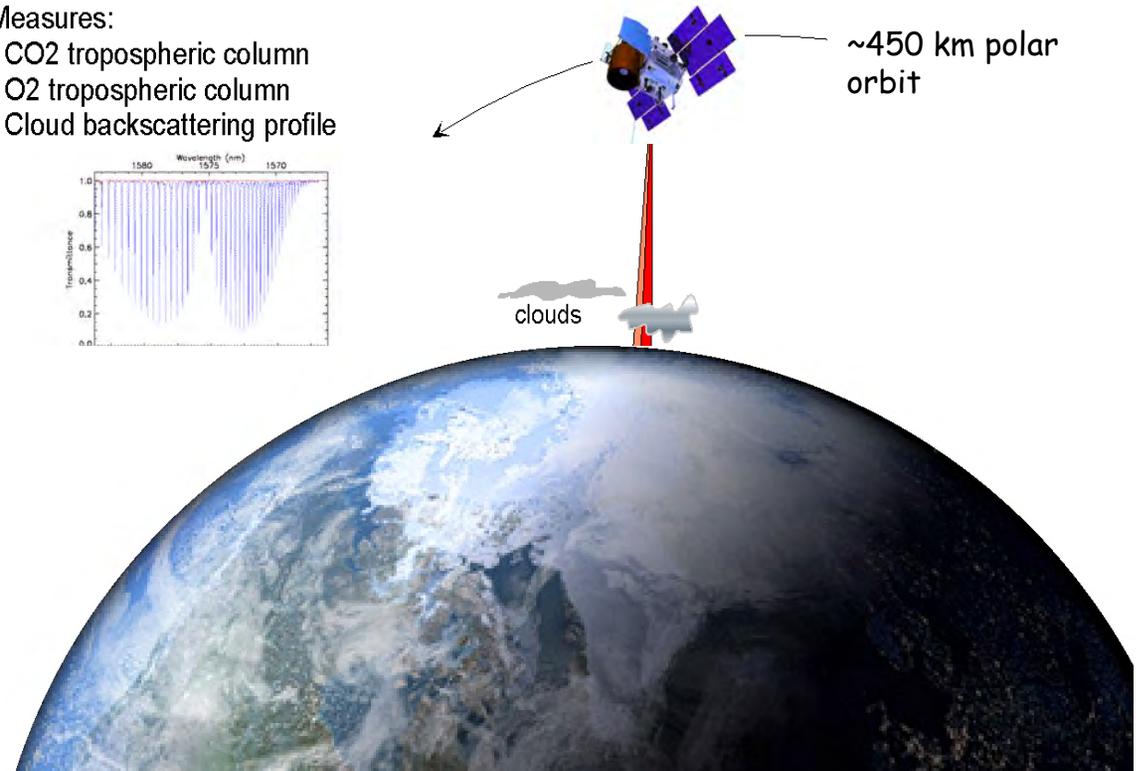
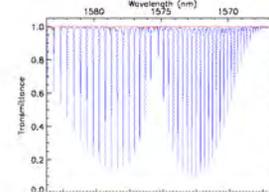
## Simultaneous laser measurements:

1. CO2 lower tropospheric column  
One line near 1572 nm
2. CO2 full column (line area)
3. O2 total column (surface pressure)  
Measured between 2 lines near 765 nm
4. Altimetry & atmospheric backscatter profile from CO2 signal:  
Surface height and atmospheric scattering profile at 1572 nm

## Measurements use:

- Pulsed lasers
- 8-10 KHZ pulse rates
- $\geq 8$  laser wavelengths for CO2 line
- Time gated Photon counting receiver

- Measures:
- CO2 tropospheric column
  - O2 tropospheric column
  - Cloud backscattering profile

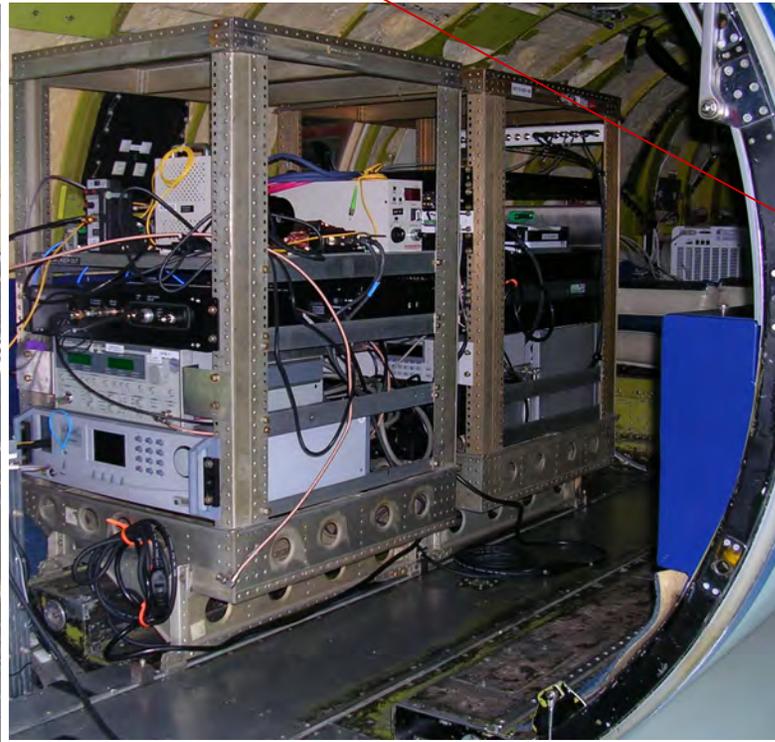
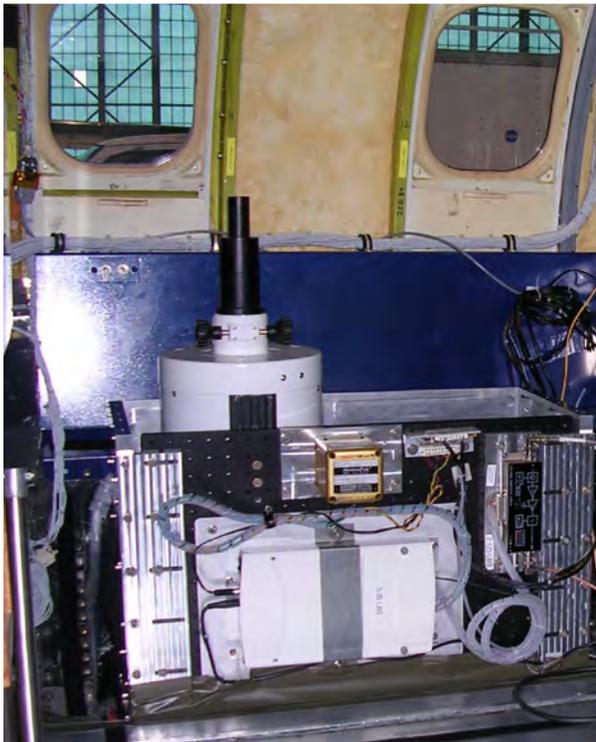


## CO2 & O2 column measurements:

- Pulsed (time gated) signals :
  - Isolates full column signal from surface
  - Reduces noise from detector & solar background
- Target:  $\sim 1$ ppmV in  $\sim 100$  km along track sample



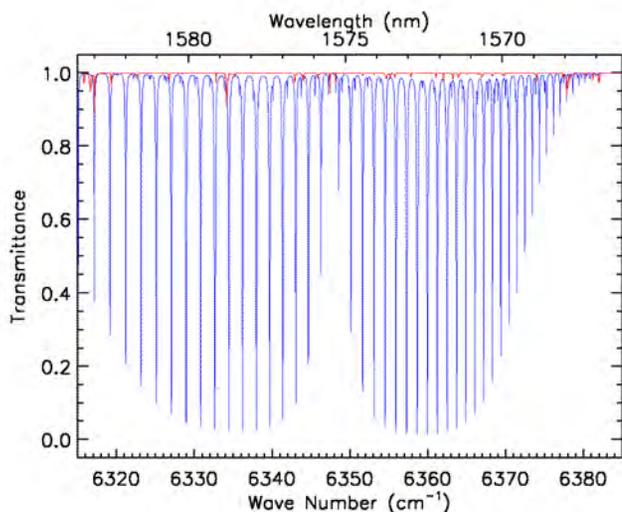
## Pulsed Airborne CO2 Sounder Instrument on the NASA Glenn Lear-25



View of nadir port showing  
transmit and receiver  
windows

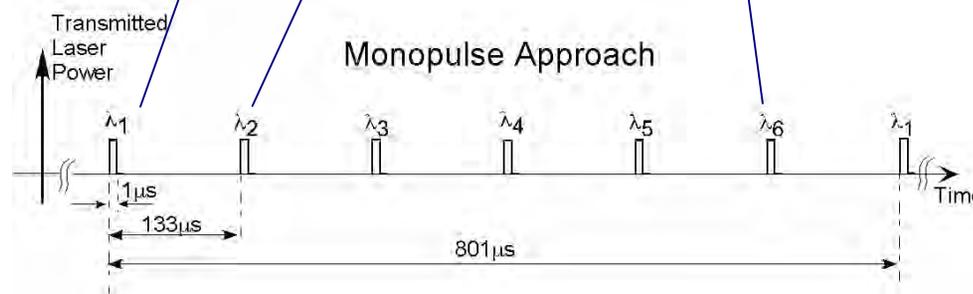
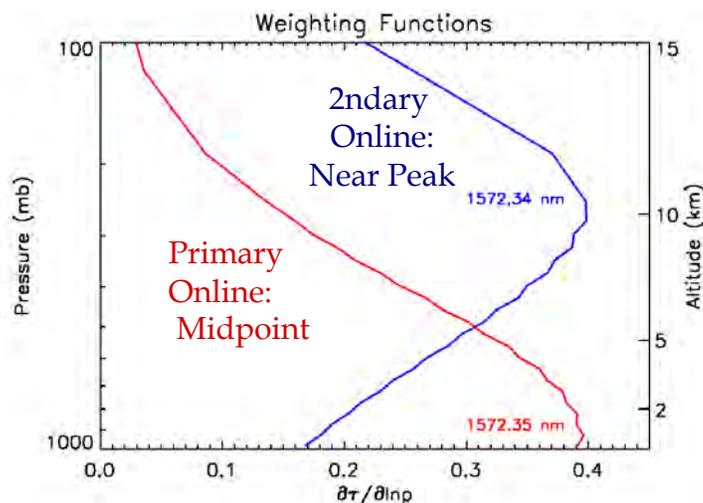
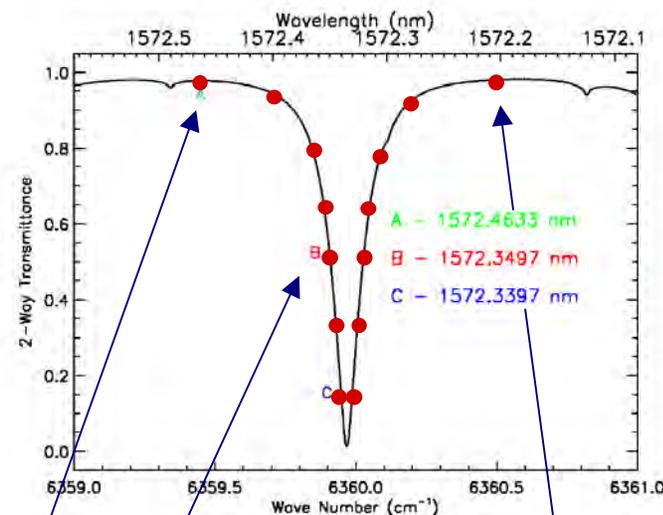


# Candidate CO2 Line, Sampling & Vertical Weighting Functions



Airborne lidar used 20 wavelength samples across line

8 samples planned for space



Multi-wavelength Line Sampling allows:

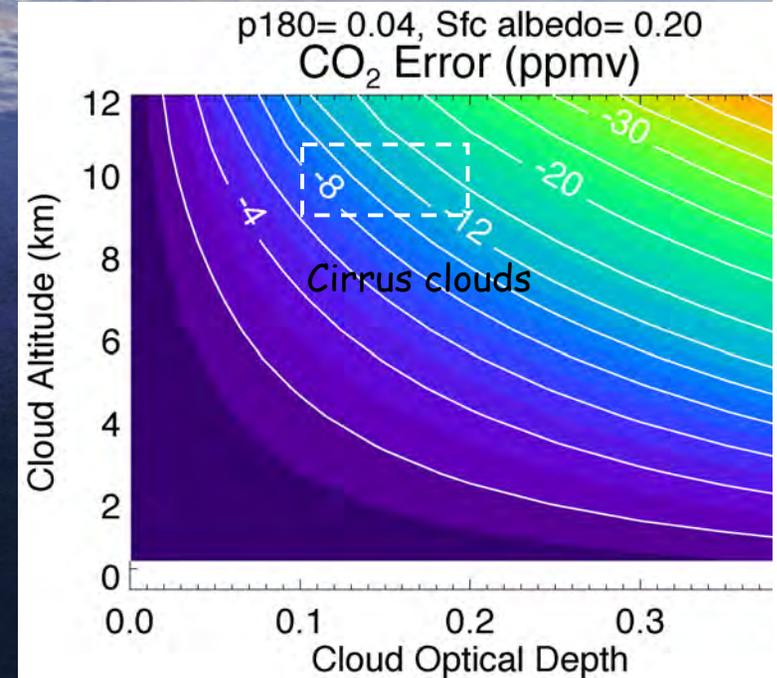
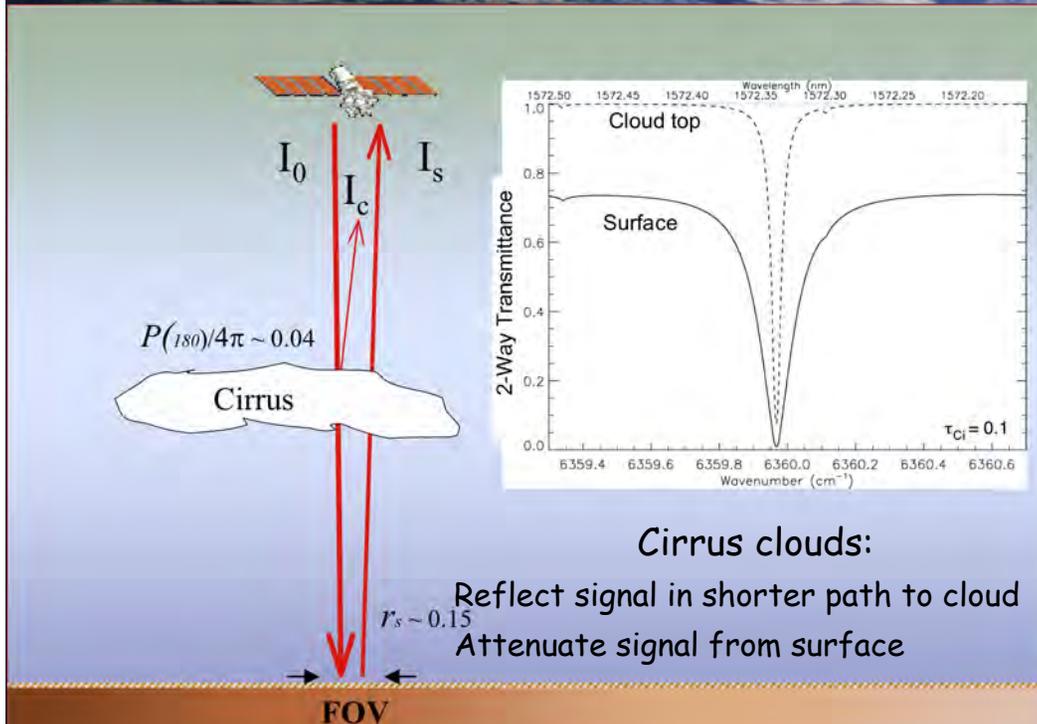
- Detection & correction of Doppler & λ errors
- Modeling -> reduces errors from varying λ response
- CO2 retrievals for: Lower troposphere
- Total column; Line shape information

Line OD area -> total column

# Why use pulsed lasers & ranging gating ?

## Atmospheric Scattering

- Thin cirrus clouds are quite prevalent,  $\beta_\pi$  varies with  $\lambda$
- Cloud reflections shorten average optical path -> bias non-gated column estimates
- Cirrus cloud scattering -> 8-14 ppm errors in non-range gated measurements
- Pulsed & range gating eliminates these errors



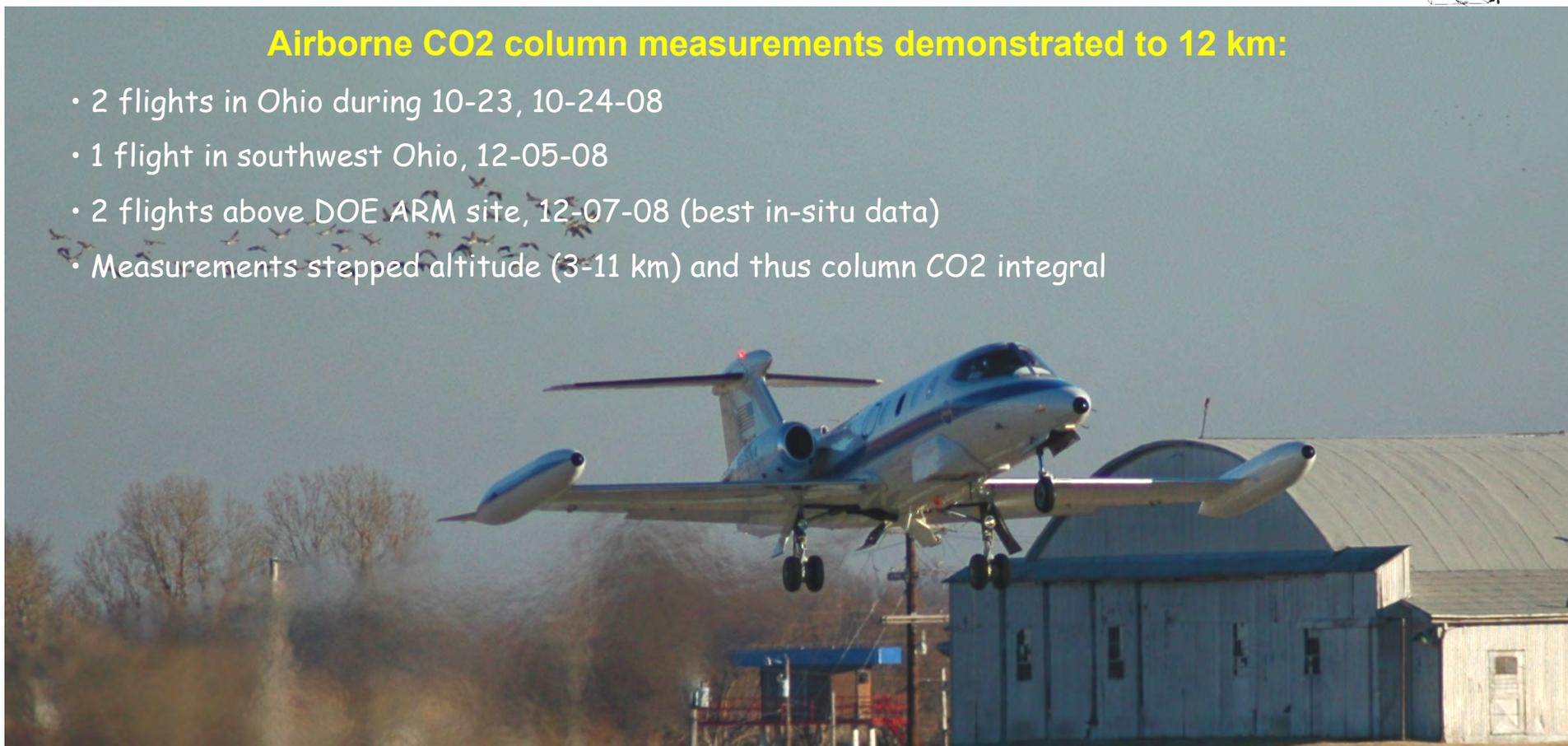


# Airborne Measurement Demonstrations - 2008



## Airborne CO<sub>2</sub> column measurements demonstrated to 12 km:

- 2 flights in Ohio during 10-23, 10-24-08
- 1 flight in southwest Ohio, 12-05-08
- 2 flights above DOE ARM site, 12-07-08 (best in-situ data)
- Measurements stepped altitude (3-11 km) and thus column CO<sub>2</sub> integral

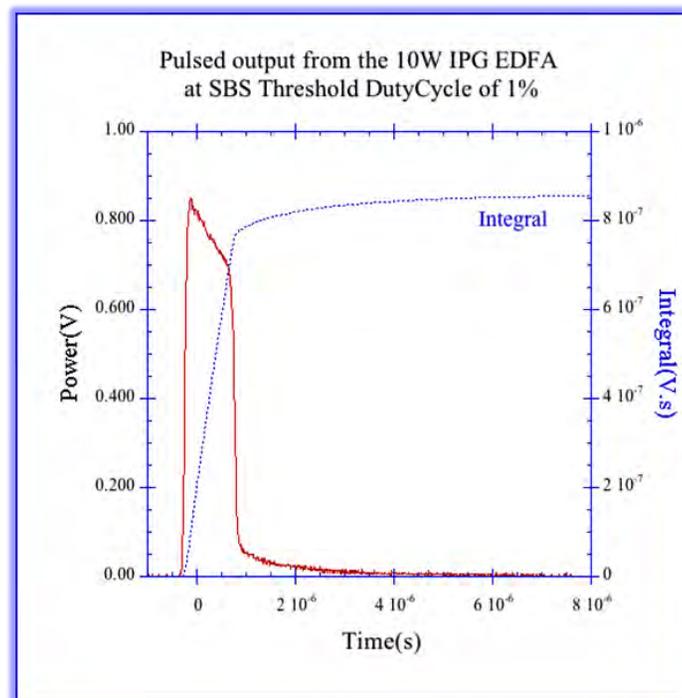
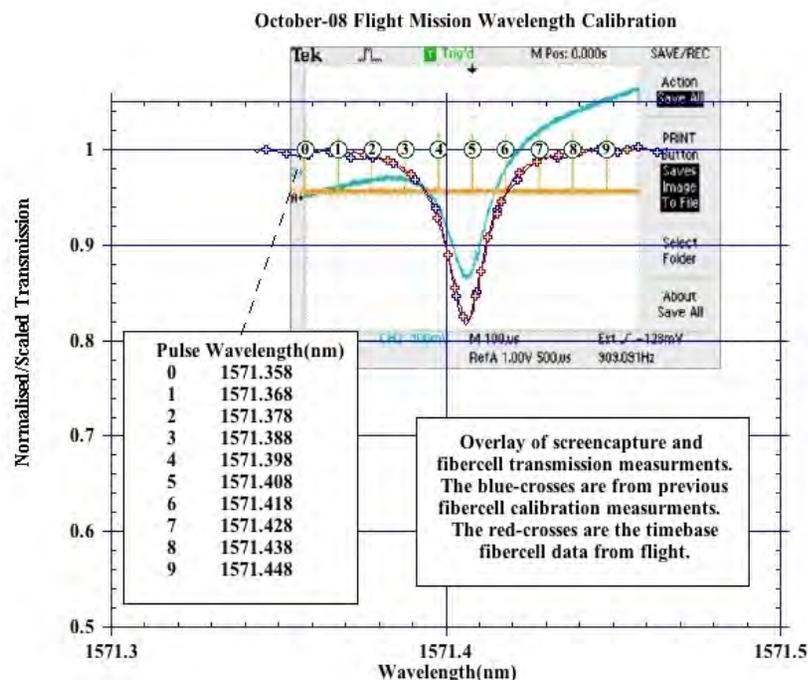


DOE ARM Site deployment:  
*Background* - NASA Glenn Lear 25 takeoff from Ponca City Airport on 12/7/08 (Graham Allan photo)  
*Left* - Goddard field experiment team  
*Right* - DOE Cessna aircraft with in-situ CO<sub>2</sub> sampler (courtesy of Sebastien Biraud/LBL)





# CO2 Line, Laser Pulses & Instrument parameters



## Instrument parameters:

Ave. Laser power: 0.24 W (24 uJ/pulse)

Wavelength scans: 20 wavelengths, 450 Hz

Telescope diameter: 20 cm

Receiver transmission: ~64%

Detector quantum efficiency: 2%

Laser divergence: 100 urad

CO2 line: 1572.33 nm

Receiver FOV: 200 urad

Receiver optical bandwidth: 800 pm

PMT dark count rate: ~500 kHz



# CO2 Sounder Summer 2009 Test & Science Flights (ASCENDS program & GSFC IRAD supported)

Improved Nadir aircraft  
windows (wedged, AR  
coated) eliminated  
etalon fringe variability  
& errors



CO2 Sounder team in OK,  
with Marc Fischer and LBL  
flask sampler

Bill & Graham after a science flight from LaRC





# 2009 Flight Example: Measuring through Cloud deck over Homer IL

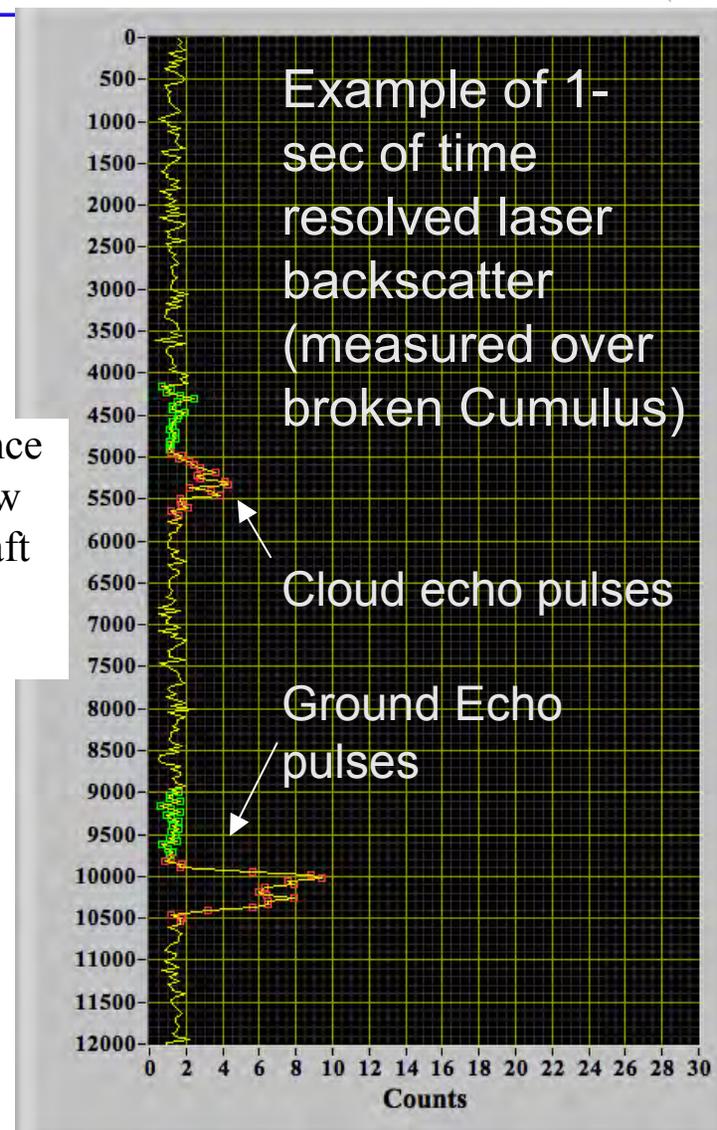


Cirrus at  
~32000 ft

Broken  
Cumulus  
~5000'

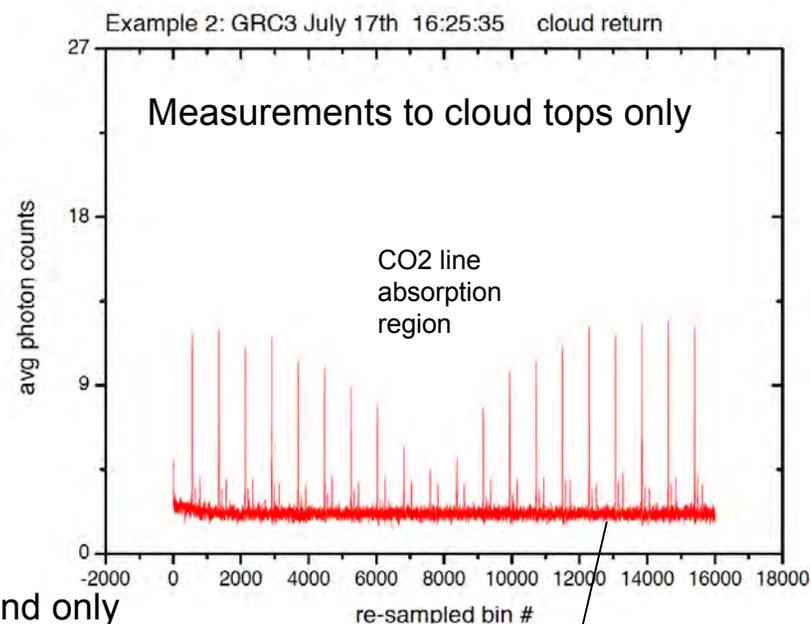
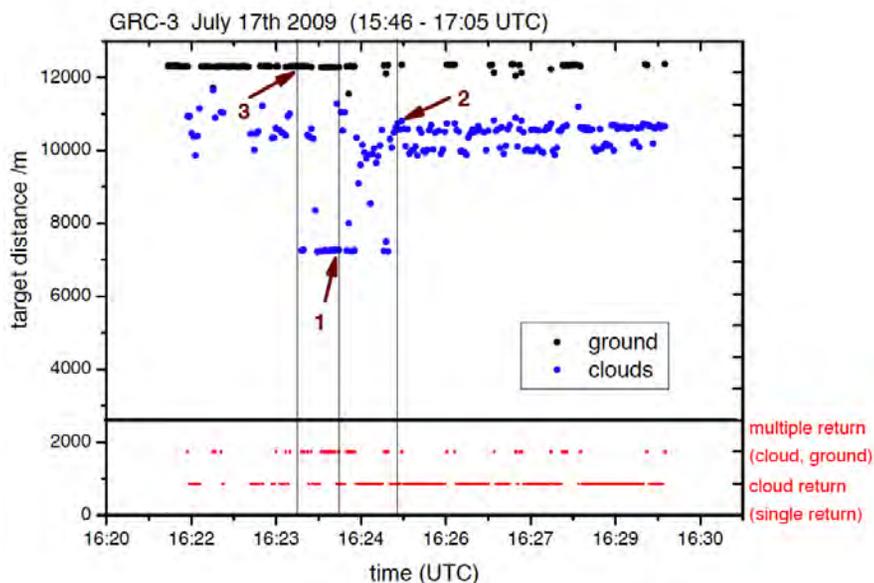


Distance  
below  
aircraft  
(ft)

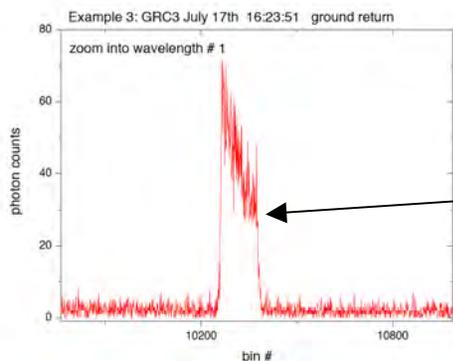




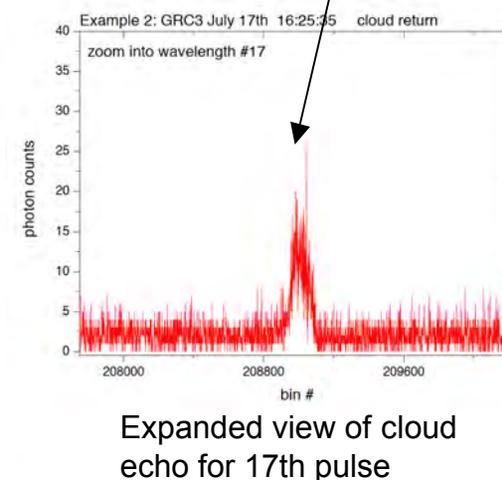
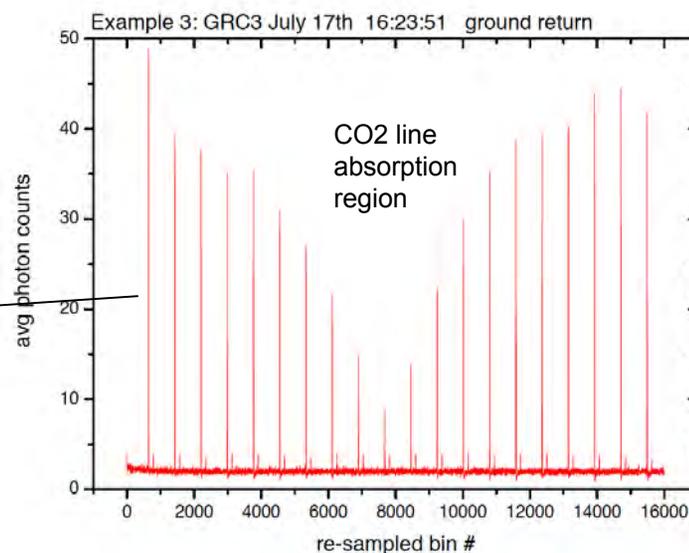
# Examples of Measurements to Ground & Clouds (uncorrected for $\tau_{\text{sys}}(\lambda)$ )



Expanded view of ground echo for 1st pulse



Measurements to ground only



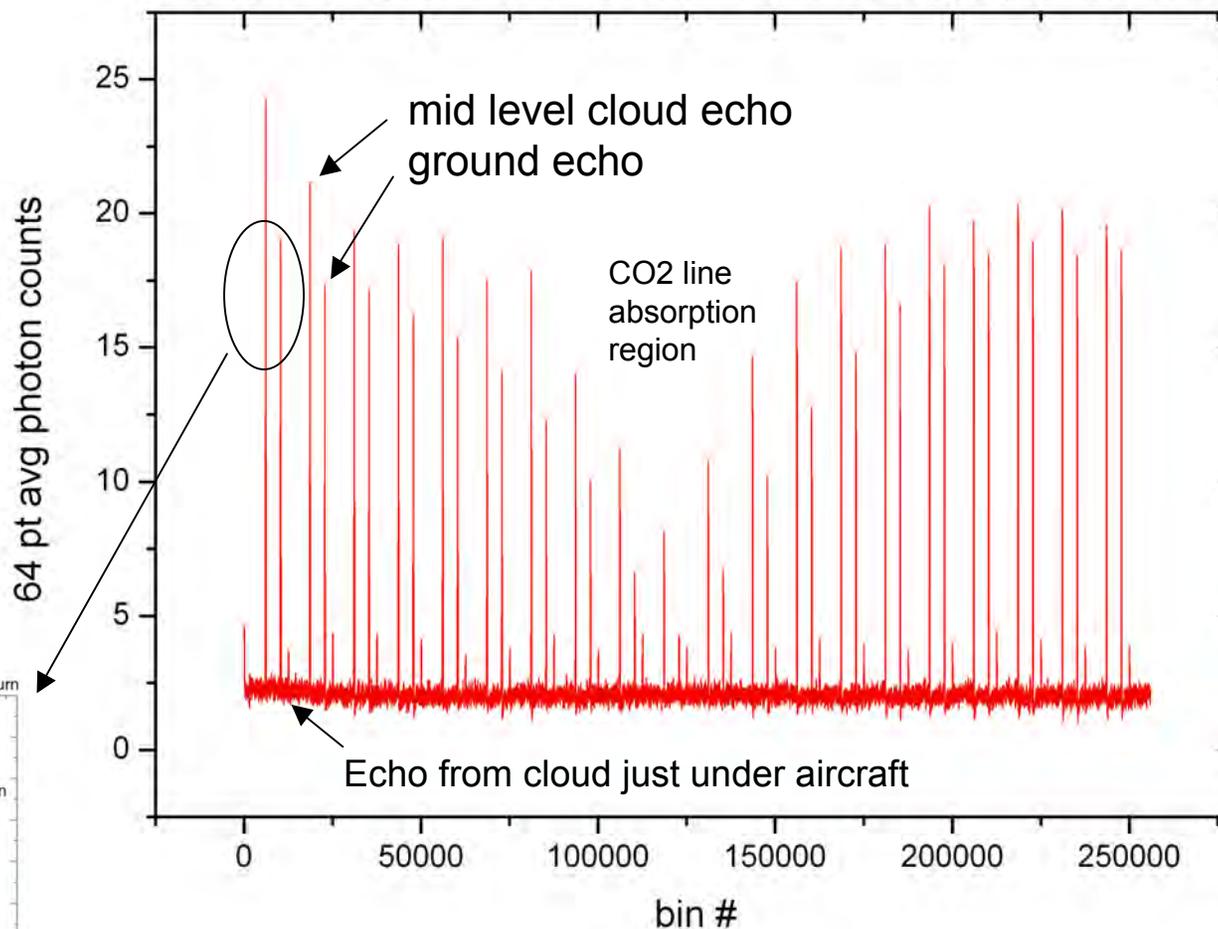


# Examples of Measurements through 2 Cloud layers (cloud, cloud, ground echo pulses)

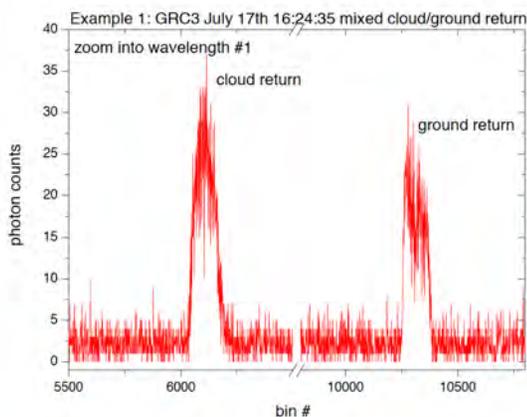


(Raw measurements uncorrected for  $\tau_{\text{sys}}(\lambda)$ )

Example 1: GRC3 July 17th 16:24:35 mixed cloud/ground return



Expanded view of 1st echo pulse group in sequence



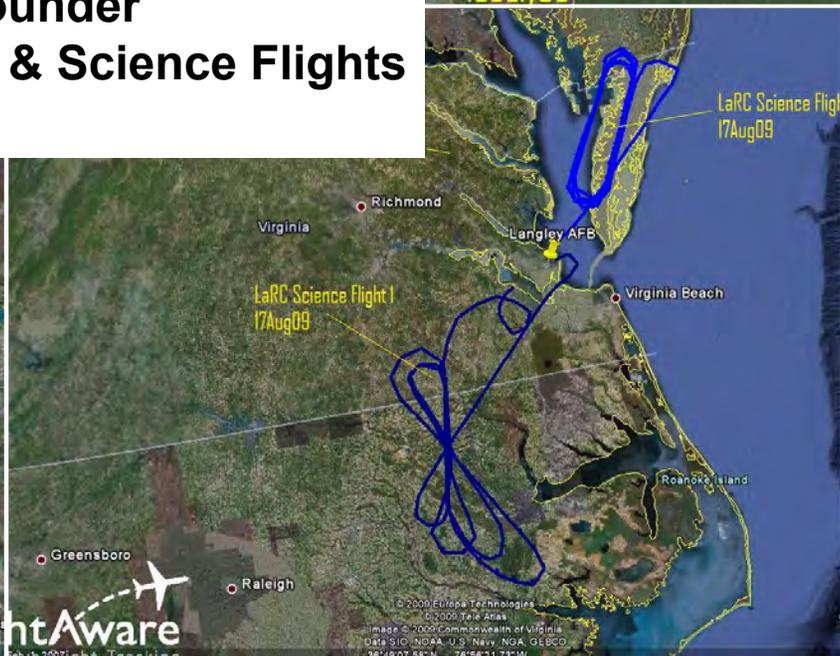
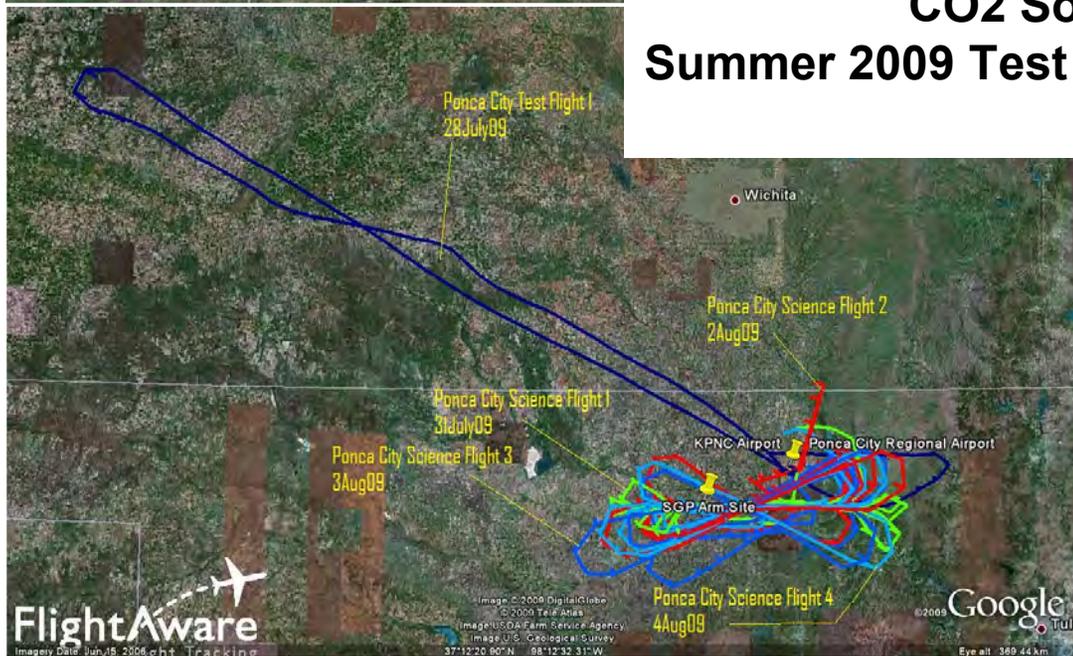
Note:

Absorption line shape to clouds - thinner, less deep

Absorption line shape to ground - broader & deeper



**CO2 Sounder  
Summer 2009 Test & Science Flights**



1. Cessna Takeoff



2. Twin Otter Takeoff



3. Lear Takeoff

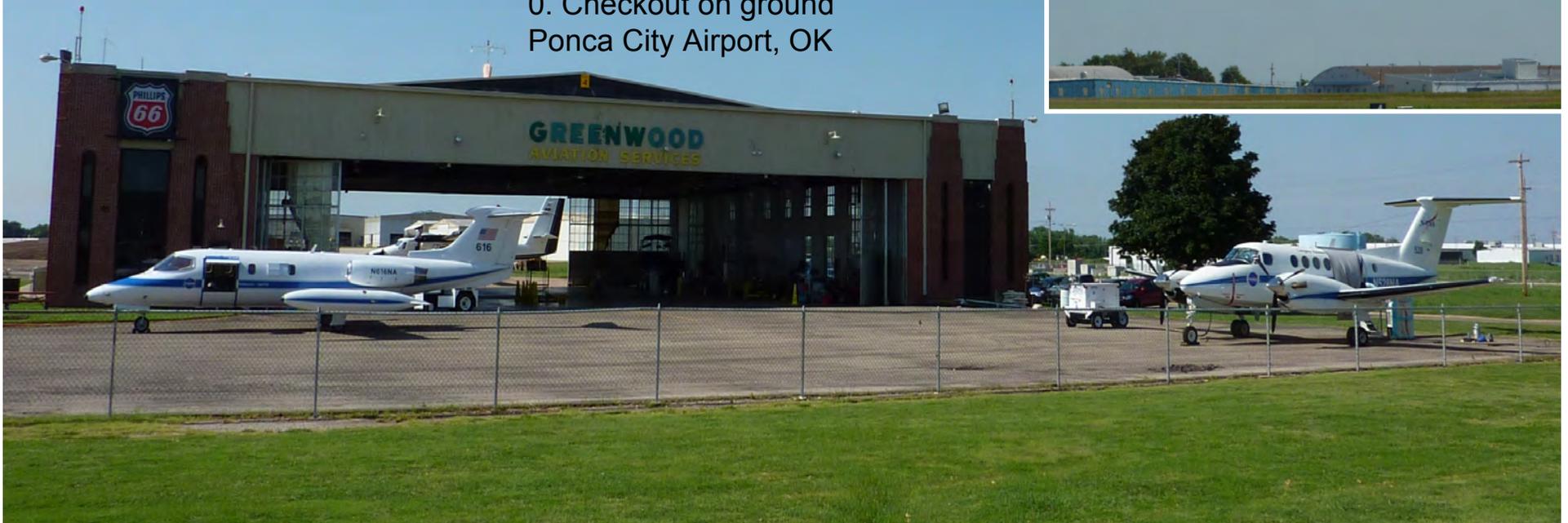


Coordinated Airborne Experiments to  
Measure CO<sub>2</sub> column densities in support  
of ASCENDS Mission Definition  
(August 2009)

4. UC-12 Takeoff



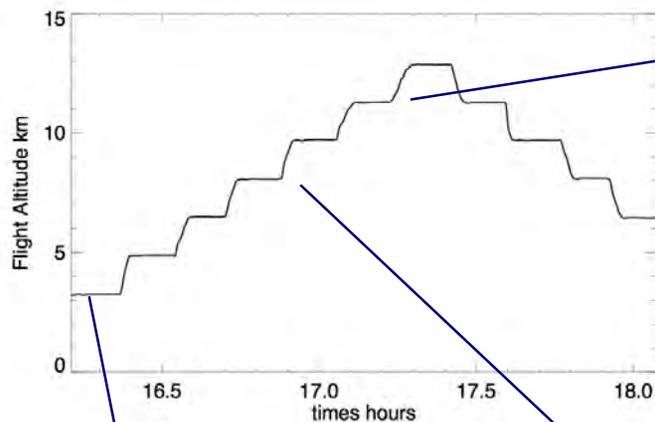
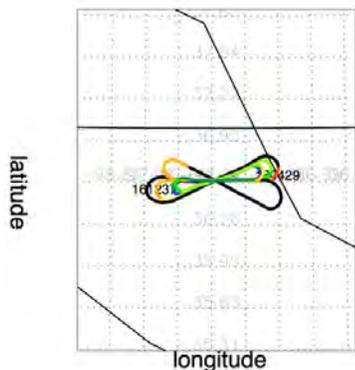
0. Checkout on ground  
Ponca City Airport, OK



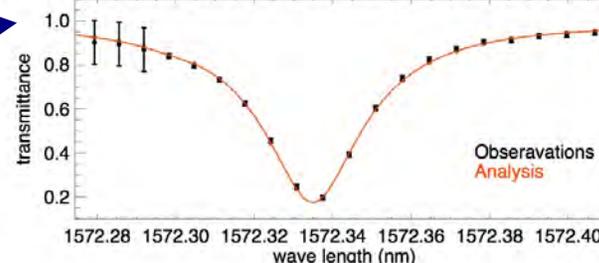


# Examples of Line shapes vs Altitude

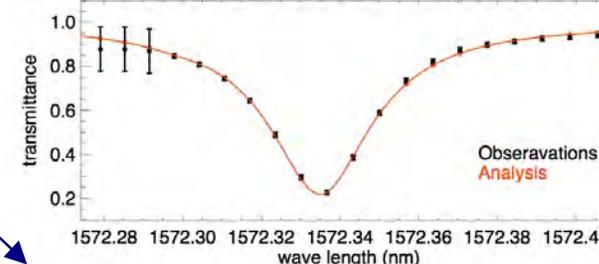
## OK SGP ARM Site Flight 4 (Up) - August 4, 2009



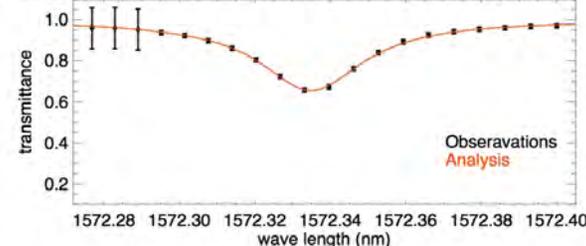
Altitude= 11.2 km Cost= 0.137 Line Shape w/o System Response



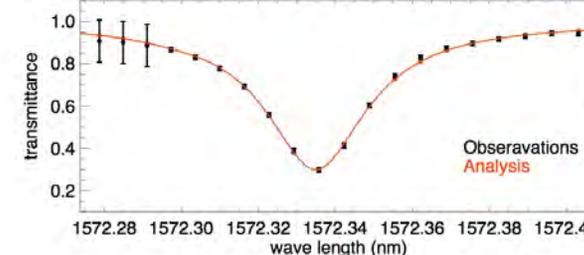
Altitude= 9.5 km Cost= 0.190 Line Shape w/o System Response



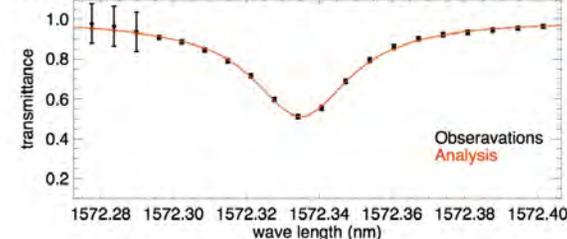
Altitude= 3.1 km Cost= 0.028 Line Shape w/o System Response



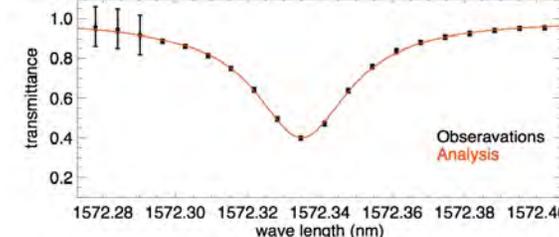
Altitude= 7.9 km Cost= 0.159 Line Shape w/o System Response



Altitude= 4.8 km Cost= 0.097 Line Shape w/o System Response



Altitude= 6.3 km Cost= 0.072 Line Shape w/o System Response



- Black dots - sampled line shape from lidar
- Typ. 60 sec ave time

• Red curves - best fit line shapes (based on HITRAN) from retrieval process

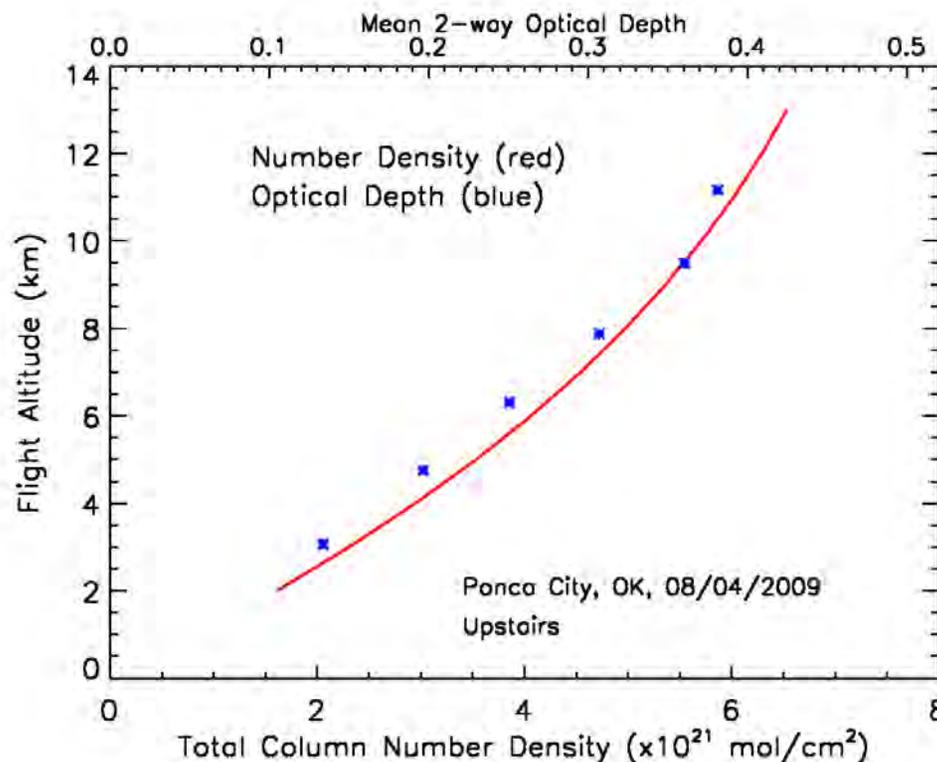
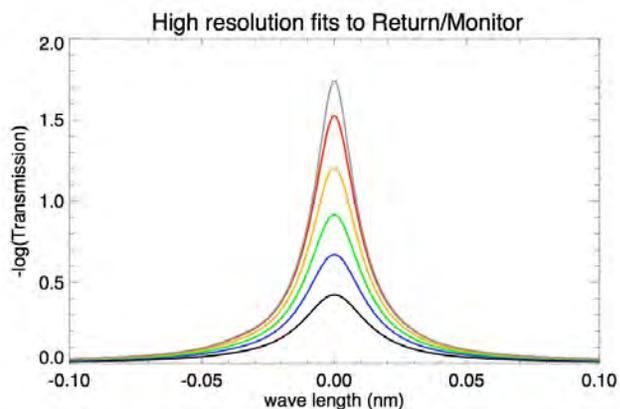
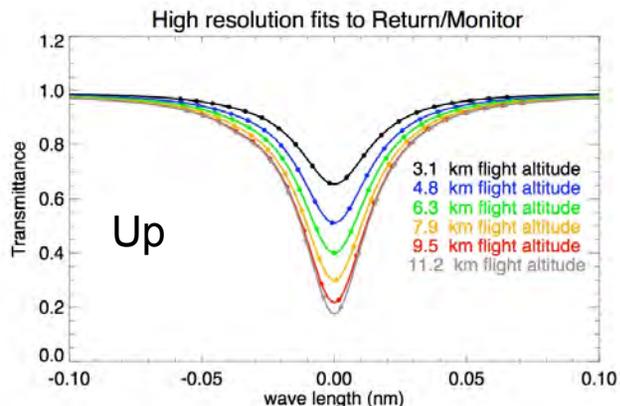
- Absorption increases with altitude
- Smooth line shapes at all altitudes !

sorption from 3-13 km altitudes



# Line Optical Density & # Density vs Altitude

## Oklahoma SGP ARM Site - Flight 4: August 4, 2009

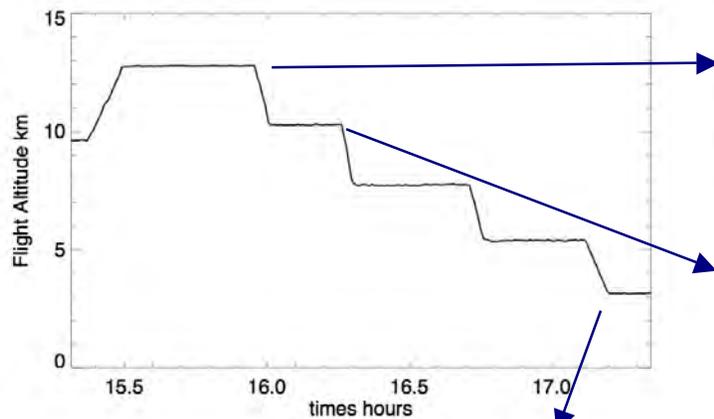
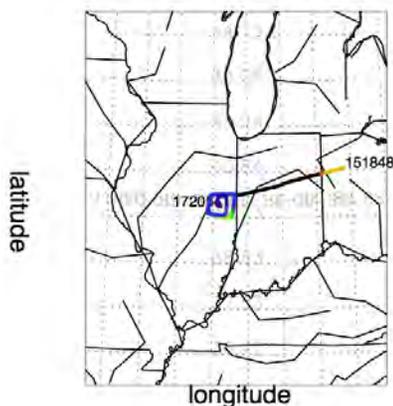


- Mean Optical Depths from line fits to CO2 Sounder measurements
- # Densities calculated from LaRC in-situ sensor and radiosonde readings

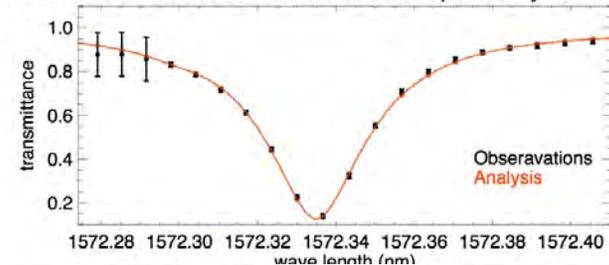


# Examples of Line shapes vs Altitude

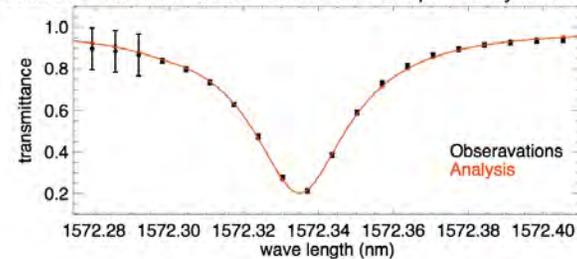
## Homer IL - August 13, 2009



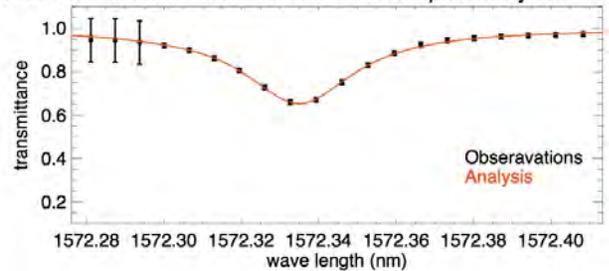
Altitude= 12.7 km Cost= 0.183 Line Shape w/o System Response



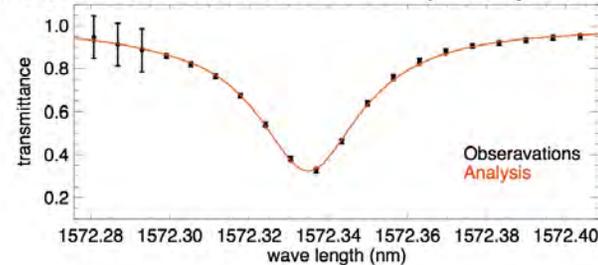
Altitude= 10.2 km Cost= 0.156 Line Shape w/o System Response



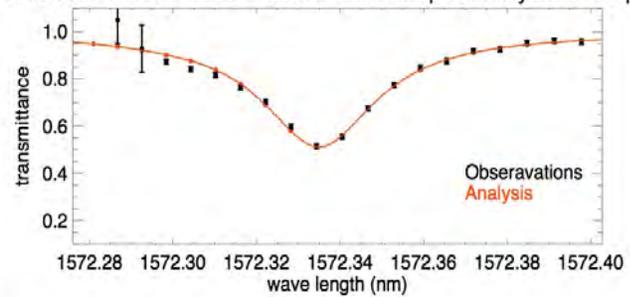
Altitude= 3.0 km Cost= 0.032 Line Shape w/o System Response



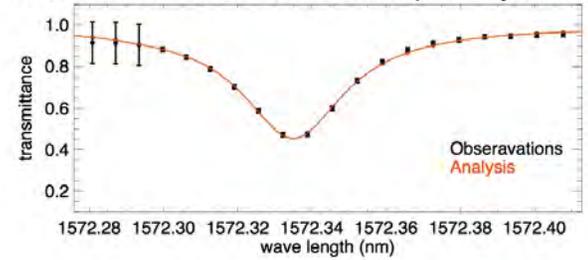
Altitude= 7.6 km Cost= 0.128 Line Shape w/o System Response



Altitude= 4.9 km Cost= 2.614 Line Shape w/o System Response



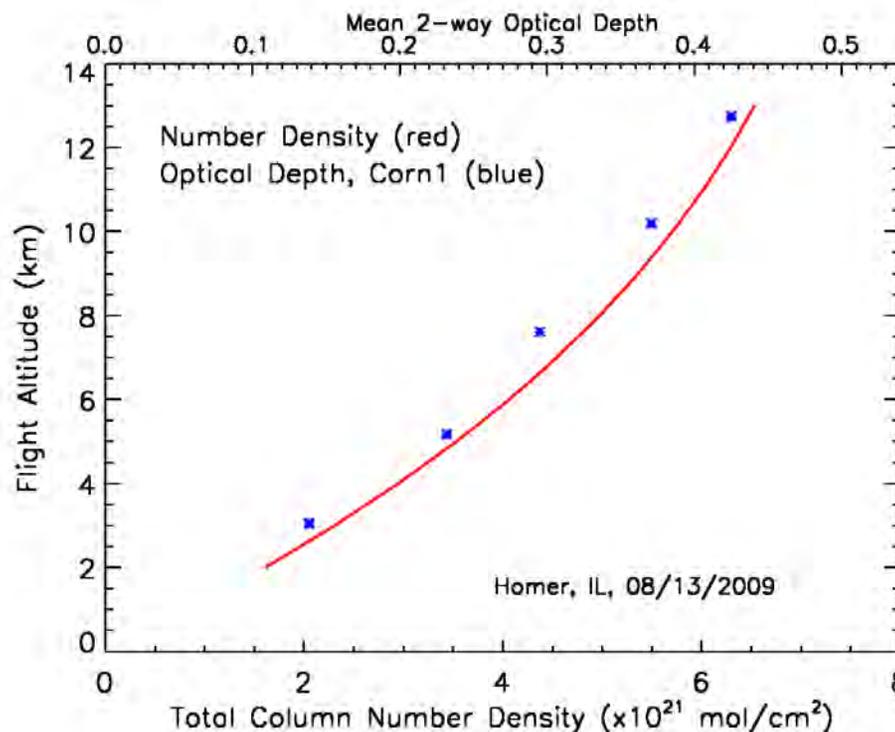
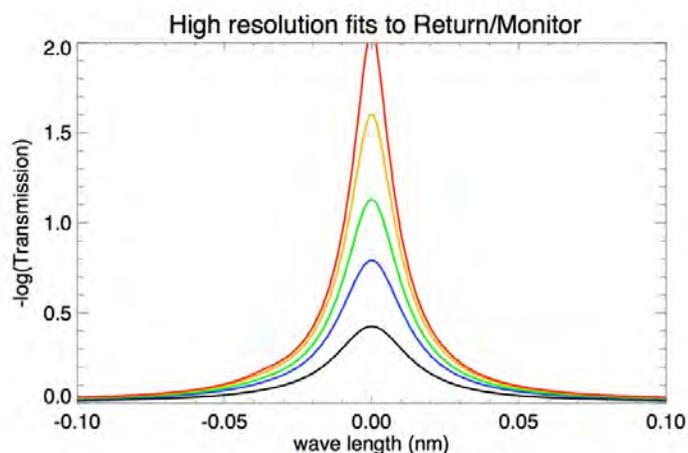
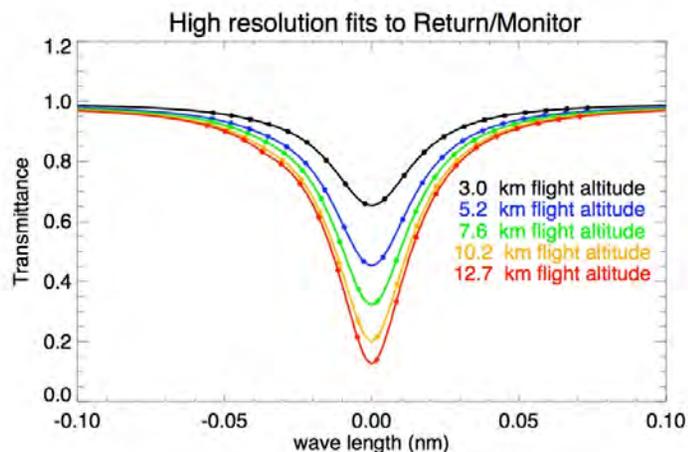
Altitude= 5.2 km Cost= 0.093 Line Shape w/o System Response



- Depth increases with altitude
- Smooth line shapes at all altitudes !



# Line Optical Density & # Density vs Altitude Homer IL Flight - August 13, 2009

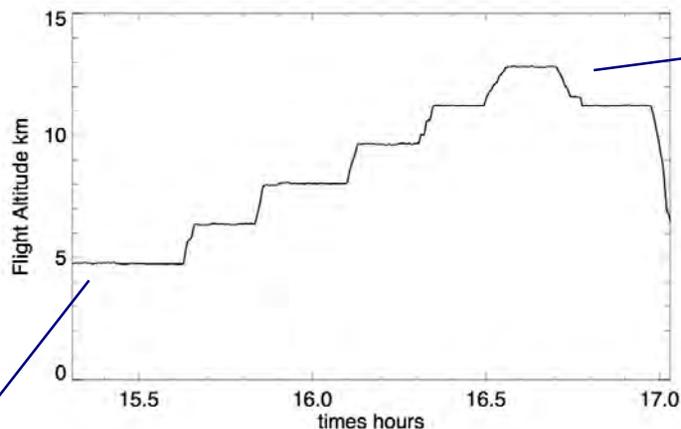
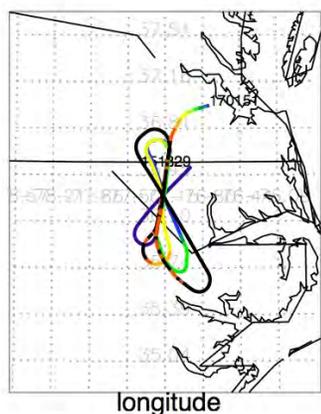


- Mean Optical Depths from line fits to CO<sub>2</sub> Sounder measurements
- # Densities calculated from LaRC in-situ sensor and radiosonde readings

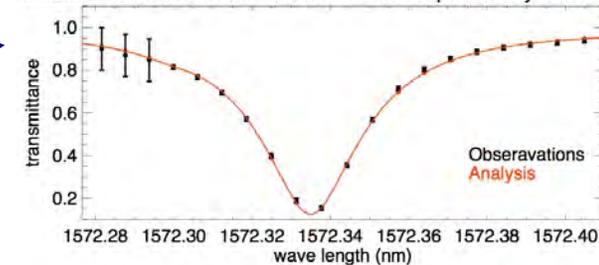


# Examples of Line shapes vs Altitude

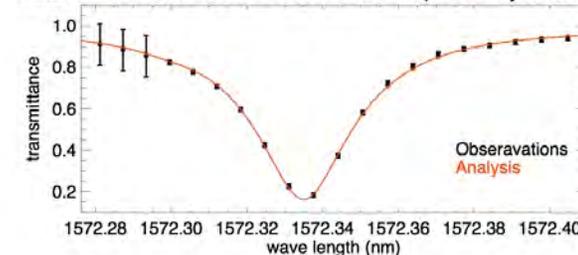
## North Carolina Flight - August 17, 2009



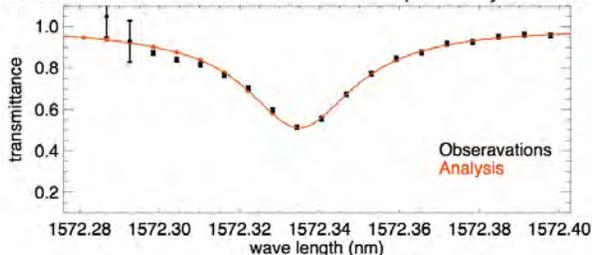
Altitude= 12.9 km Cost= 0.156 Line Shape w/o System Response



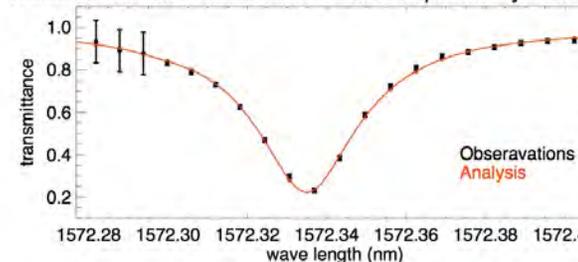
Altitude= 11.5 km Cost= 0.155 Line Shape w/o System Response



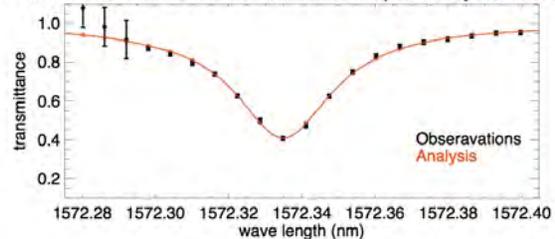
Altitude= 4.9 km Cost= 2.614 Line Shape w/o System Response



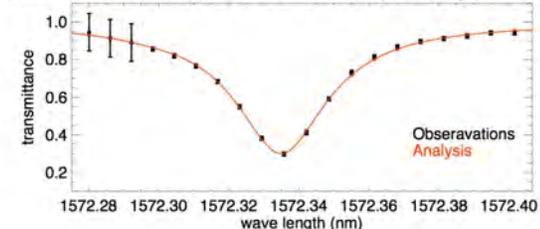
Altitude= 9.8 km Cost= 0.181 Line Shape w/o System Response



Altitude= 6.4 km Cost= 0.401 Line Shape w/o System Response



Altitude= 8.1 km Cost= 0.117 Line Shape w/o System Response



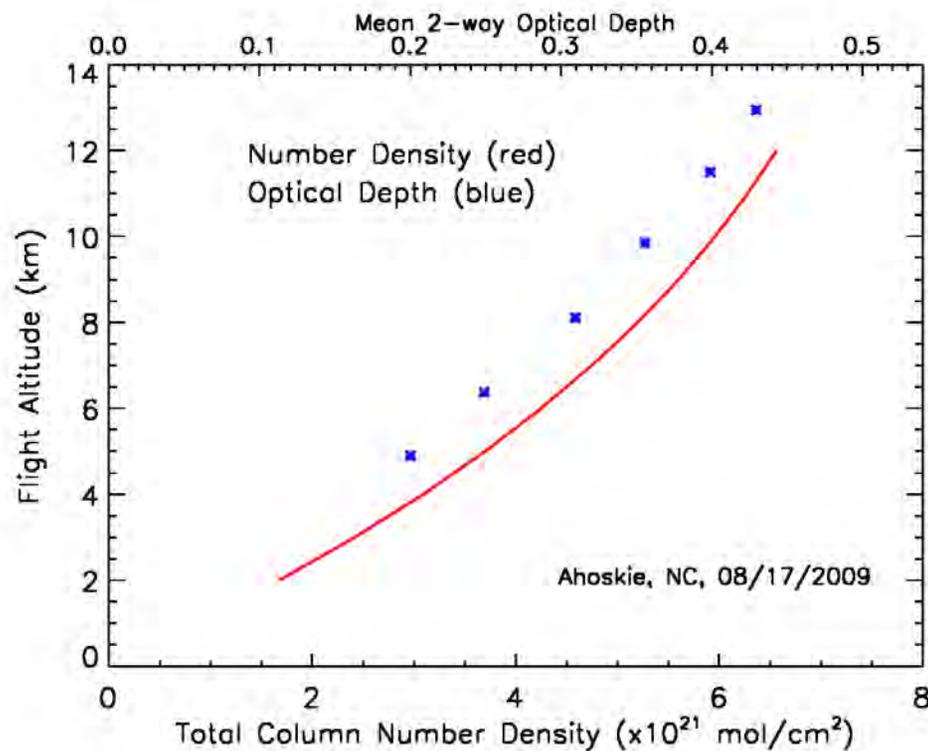
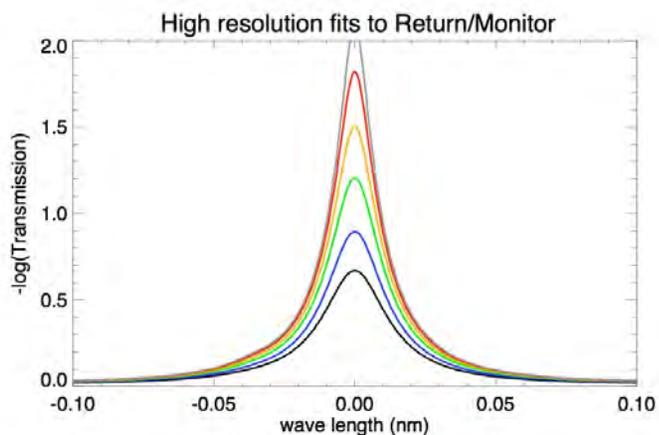
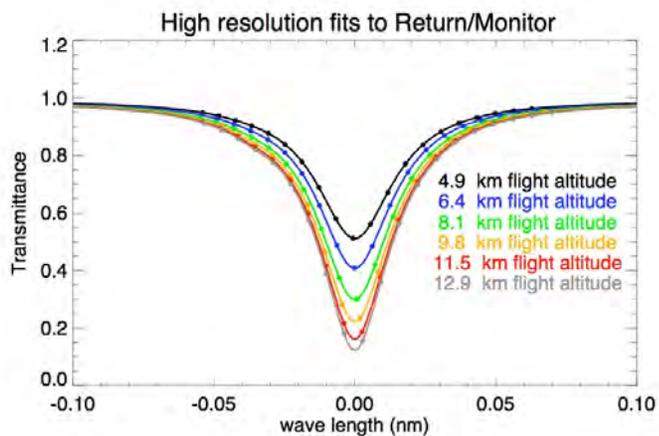
3/15/10

- Depth increases with altitude
- Smooth line shapes at all altitudes !

tion from 5-13 km altitudes



# Line Optical Density & # Density vs Altitude North Carolina Flight - August 17, 2009



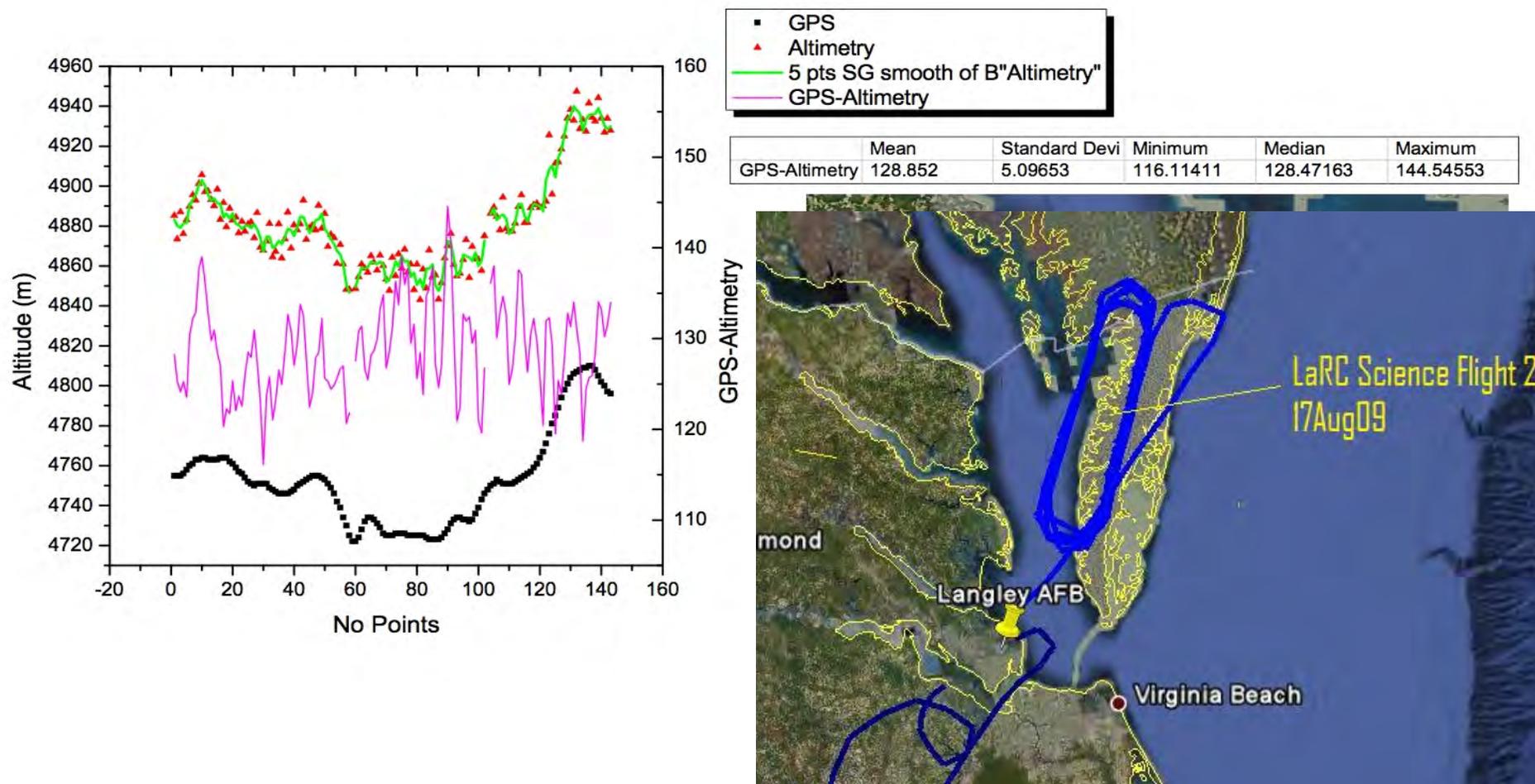
- Mean Optical Depths from line fits to CO<sub>2</sub> Sounder measurements
- # Densities calculated from LaRC in-situ sensor and radiosonde readings



# Example - Altimetry measurement segment: 8/18/09 Flight



- Initial look at altimetry measurements (time of flight) for over water segment of the last flight (Eastern Shore VA)



# Summary

- Demonstrated a new pulsed lidar for measuring CO<sub>2</sub>:
  - 20 samples across line, 450 Hz line scan rate
  - 25 uJ/pulse, photon counting PMT receiver
- Fall 08:
  - 1st Airborne measurements of CO<sub>2</sub> line shape:
  - Over land, vegetation (trees), water
  - Good SNR & N<sub>CO<sub>2</sub></sub> agreement (A/C window limits)
  - Good line shape & conc. (~6 ppm) agreements
- Summer 09 - Improved lidar & window
  - 9 science flights, 6 coordinated with LaRC, JPL
  - Line shapes measured to & through clouds
  - Good OD agreement with N<sub>CO<sub>2</sub></sub> from in-situ
  - Calibration is underway

